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Confinement jumps in a non-neutral plasma

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Measurements of confinement jumps in pure electron plasmas confined on magnetic surfaces are presented and discussed. The experiments were performed in the Columbia non-neutral torus stellarator [T. S. Pedersen, J. P. Kremer, R. G. Lefrancois, Q. Marksteiner, N. Pomphrey, W. Reiersen, F. Dahlgren, and X. Sarasola, Fusion Sci. Technol. **50**, 372 (2006)]. The jumps exhibit hysteresis and are associated with a negative differential resistance. The jumps occur at particular emission currents of the biased emissive filaments that create and sustain the electron plasmas independent of the methods used to affect the emission current. This observation, as well as other experimental evidence, supports that the jumps are caused by a cathode instability. The jumps can also be triggered by the application of a bias potential on a nearby mesh. In most circumstances, the jumps occur between two stable but measurably different equilibrium states. These different equilibrium states have substantially different confinement times. The cathode physics is important for the jumps because the cathode instability provides the perturbation that triggers the jump of the whole plasma into the other equilibrium state, but as mentioned, an external electrostatic perturbation is also capable of triggering such a jump. © *2009 American Institute of Physics*.

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I. INTRODUCTION

Jumps in the cathode characteristic have been observed in both neutral and non-neutral plasmas.[1–11] These jumps have been studied in a variety of contexts. Some have studied the phenomenon in quasineutral plasmas, generally explaining the jumps in terms of processes that enhance ionization.[1–3] Others have used the occurrence of jumps and associated oscillations to study nonlinear processes such as chaos and self-organization[2,4,5] or found an application for catastrophe theory.[6] In non-neutral plasmas, sudden jumps in the emission current were observed when studying a method for mapping the magnetic surfaces in a stellarator.[7,8] Those studies focused on describing the characteristic and determining whether it was a problem for the surface mapping method rather than studying the jumps themselves. Those investigations showed that the voltage at which the jump occurs depends on certain parameters and suggested that the jump is caused by the action of a virtual cathode.

In this paper we present results from a study of the current jumps in non-neutral plasmas confined in a stellarator, the Columbia non-neutral torus (CNT). The experiment has been described in Ref. 12, and the main results from non-neutral plasma experiments so far are summarized in Ref. 13. The experiments presented here are quite similar to those described in Refs. 7 and 8, but our experiments were performed to investigate the physics of the jumps themselves.

For these experiments in CNT, the electron source is a small heated biased cylindrical spiral filament 1 mm in diameter and 2 mm in length. Filaments are attached to insulating rods inserted into the plasma. These rods are known to be perturbing—they charge negative and cause cross-field $\mathbf{E}\times\mathbf{B}$ transport. They also prevent the accumulation of ions in the plasma. When an ion strikes the insulating rod, it is neutralized.[14] CNT operates with a steady state ion fraction that is determined by the dynamical balance between volumetric ionization of background neutrals and recombination on the internal rods. The steady state fraction can be controlled by changing the neutral pressure (changing the ionization rate) and by insertion or retraction of rods (changing the recombination rate). For usual operating parameters, the ion fraction is less than 1%.

We present the results of experiments concerning the emission current jump and its properties. The results will be discussed and compared to the phenomenologically similar effect observed in neutral plasmas. The plausibility of an explanation for the transport jump in terms of a cathode sheath instability will be discussed. The properties of the stable equilibrium states are then presented. We show that it is possible to switch between stable transport states using methods unrelated to the cathode instability jumps. We conclude that a set of stable equilibrium states exists, and that the cathode instability is one of several perturbations that can cause a shift between these states.

II. PROPERTIES OF JUMPS

In the experiments described here an electron plasma is created from the biased emissive (hot) filament and the emission current is measured. Plasmas created in this way are in a steady state. By continuity the emission current is the same as the loss rate of electrons from the plasma, which is the same as the cross-field transport rate integrated over a magnetic surface. As mentioned, the ion fraction is also in steady state.

Jumps in CNT were first observed as discontinuities in the cathode characteristic as the bias potential was increased (Fig. 1). Since these are jumps in the emission current, they

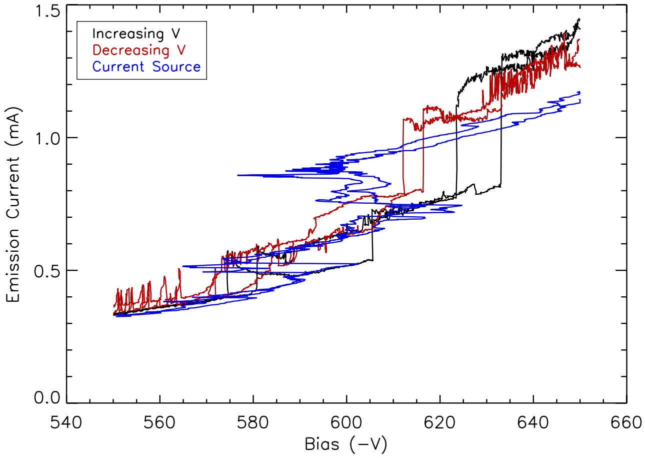

FIG. 1. (Color online) The hysteresis effect and negative differential resistance are shown here. As the cathode potential is increased using a voltage controlled source (black), the current increases in a discontinuous jump. If instead the cathode potential is decreased (red), the jump back down occurs at a lower voltage. Sometimes there is no downward jump and the curve smoothly reaches the prejump curve at a lower voltage. A current source characteristic (blue) reveals the negative differential resistance. The different curves for different experiments indicate the amount of reproducibility of the characteristics.

reflect an increased loss rate of electrons from the plasma. The sharp discontinuity in the characteristic shows that the bias potential is nearly constant during the change.

The jumps also happen when the bias potential is decreased (Fig. 1). The emission characteristics for the decreasing and increasing biases show that the jumps exhibit hysteresis. For similar jumps in neutral plasmas, the hysteresis is a reflection of a negative differential resistance in the cathode characteristic. This is also the case here. In order to measure the region of negative differential resistance, a current controlled power source for the emitter was used instead of a voltage controlled source. This prevents jumps in the current, and thus allows one to measure the region of the characteristic that is unstable and therefore inaccessible for a voltage controlled source. The curve obtained with a current controlled source in Fig. 1 confirms that there is a negative differential resistance in the vicinity of the jumps. As expected, the jumps seen with a voltage controlled source occur between the stable legs, i.e., the regions of the characteristics with positive differential resistance, and bypass the unstable, negative differential resistance part of the curve.

Increasing the emitter bias is one of several experimental ways to cause a jump. The emission current and confinement time are affected by several factors besides the emitter bias. The jumps occur as the emission current increases above a certain critical value irrespective of the method used to affect confinement. Jumps are observed when the neutral pressure is increased while the cathode potential remains fixed. The increasing neutral gas pressure increases the collision rate and drives transport, as already discussed in some detail in Ref. 15. Jumps are also seen when an insulated rod is inserted deeper and deeper into the plasma. The rod drives $\mathbf{E}\times\mathbf{B}$ transport across the surfaces, which affects a larger volume of the plasma as the rod is inserted. This transport mechanism was first reported in Ref. 16 and is discussed in detail in Ref. 15.

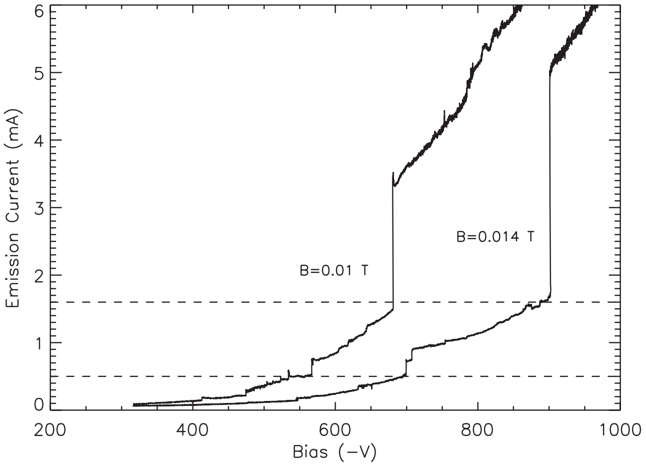

FIG. 2. Two cathode characteristics, showing that jumps occur at particular currents and that the relative magnitudes of jumps that occur at the same current are roughly similar. These features allow identification of jumps in shot-to-shot measurements. In this particular case the measurements are at two magnetic field values: $B=0.01$ T and $B=0.014$ T.

That the insertion of an extra rod causes a jump implies that ions do not play an important role for these jumps. While increases in neutral pressure or cathode bias act to increase the ion content of the plasma, the insertion of an extra insulated rod reduces the ion content.[14] Since the jump occurs at the same emission current in both cases, ions cannot be important for the jumps.

The emission current at which the jump occurs is almost the same whichever method is used to drive transport. Experiments were done to test whether the emission currents of the jumps were constant across parameters such as magnetic field strength and neutral pressure of nitrogen (N_2) or hydrogen (H_2). The set of parameters was fixed and cathode current-voltage characteristics were measured. Whenever jumps occurred they started at the same particular emission currents. An example is shown in Fig. 2.

When varying any of the parameters that affect transport, and therefore the emitter current, we observe the jumps at these specific current levels. In Fig. 2, the jumps occur at the same emitter current for two different magnetic field strengths. The jumps necessarily occur at different bias voltages in these experiments, since the higher magnetic field improves confinement and one must increase the bias voltage to increase the electron inventory, so the required emitter current is increased up to the critical level. Similarly, when operating with an increased neutral pressure, which degrades confinement, one applies a smaller bias voltage to reach the same current which then triggers a jump.

III. CRITICAL CURRENTS VERSUS CRITICAL TRANSPORT RATES

The experimental observations presented so far show that there are (at least) two self-consistent solutions to the cathode-plasma sheath physics and the radial transport. The jumps between these two stable operating points can be interpreted in several ways. The filament emission current is equal to the radial transport rate of the electrons, since the experiments are in steady state, persisting for seconds to hours. Since the emission current is tied to the radial transport rate it is not clear from the data presented so far whether it is a critical radial transport rate or a critical filament emission current, which determines the point at which a jump occurs. It is clearly important to distinguish between these two possibilities. The first one is similar to what is empirically observed for the *L*- to *H*-mode transition in quasineutral tokamak plasmas,[17] which, at least in some experiments, depends on the critical power flux through the edge region.[18] The second possibility is consistent with a local cathode sheath instability. Experiments shedding light on this issue will be described in the following.

A. Local effects

The critical currents at which the jumps occur are independent of certain aspects of the equilibrium. For example they are independent of emitter location. This was shown by emitting from filaments at different radial locations. For example, one filament located deep inside the confinement region, that is, near the magnetic axis, and one that is located radially far from the axis have transport jumps that start at the same currents. A close-fitting conducting boundary conforming to the last closed flux surface was recently installed.[19] The boundary increased the electron inventory given a particular central electrostatic potential by more than a factor of 2. Upward transport jumps are still observed to start at the same critical currents as for the previous nonconforming boundary condition despite the equilibria being substantially different. There are some qualitative changes after the installation of the mesh, most notably that the hysteresis is vastly reduced.

B. Cathode sheath instability causes the confinement jump

A simple way to break the correlation between the emitter current and the radial electron loss rate is to have several electron sources, that is, several emitting filaments capable of supplying electrons to the plasma, instead of just one. If the jump occurs at a critical radial transport rate, it will occur at a particular *total* emission current, $I_{\text{total}}=I_1+I_2=I_{\text{crit}}$, with I_1 and I_2 being the emission currents of the two filaments. If the jump is due to a cathode instability, the jump will occur when an individual emitter exceeds the critical current, $I_1 \geq I_{\text{crit}}$ or $I_2 \geq I_{\text{crit}}$, as long as the emitters are physically far enough apart that their sheaths do not overlap. A series of experiments with two emitters was performed with one emitter connected to a current controlled source and the other to a voltage controlled source. These show that it is the current going through the probe sheath, I_{sheath}, that determines whether a jump occurs. When the two emitters are placed physically far apart, i.e., with nonoverlapping cathode sheaths, the jumps occur when one of the emitters exceeds the critical current. This happens whether the emitters are on different magnetic surfaces (Fig. 3) or on the same magnetic surface (see Sec. IV).

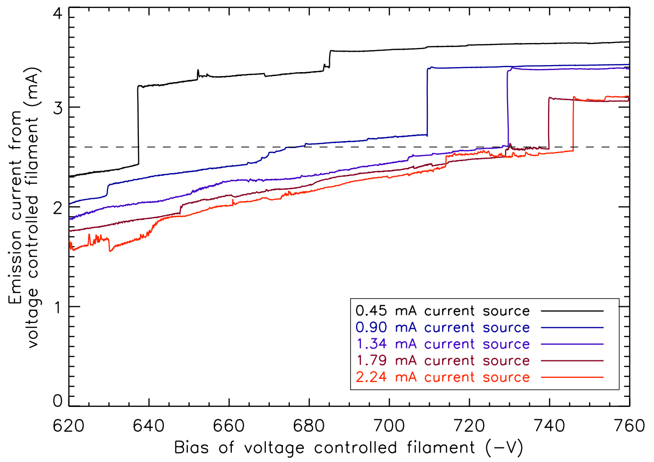

FIG. 3. (Color online) When two emitters are used transport jumps occur when one of the emitter currents exceeds the critical value. The jumps are independent of the total transport rate I_{total} in this case. Note that the y axis indicates current on the voltage controlled emitter.

When the two emitters are within a few centimeters of each other, and at the same time aligned to be on the same magnetic surface, so that they are within the same sheath, the jumps occur for $I_{\text{total}}=I_{\text{crit}}$ (Fig. 4). So, for all these different cases, we find $I_{\text{sheath}}=I_{\text{crit}}$. We conclude that the jumps are caused by a sheath instability.

IV. CHARACTERIZATION OF THE EQUILIBRIA ASSOCIATED WITH THE DIFFERENT CONFINEMENT STATES

Because the current jumps reflect a change in transport they are expected to be accompanied by a change in the equilibrium of the plasma. To study this change, measurements of the equilibrium in the two different transport states were done. To make the comparison as clear as possible, the two equilibria were obtained with the same emitter bias voltage of 525 V, which means that the central plasma potential is very close to 525 V in both cases. This was easily achieved by taking advantage of the hysteresis; by ramping the voltage

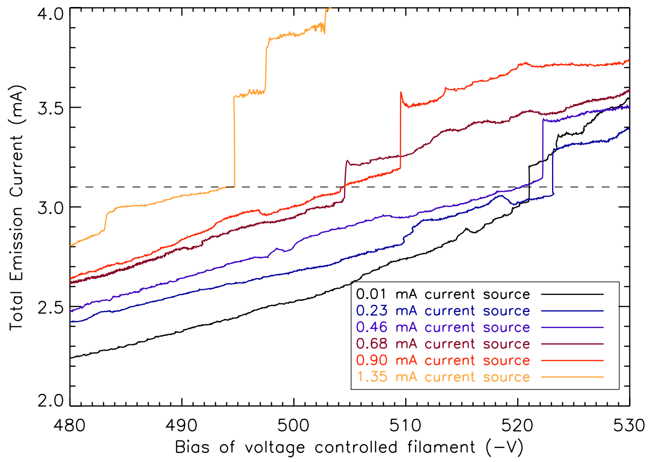

FIG. 4. (Color online) When two emitters are aligned to be in the same sheath jumps depend on the total current instead of the individual currents. Note that the y axis here is the total current I_{total} which is equal to I_{sheath} in this case.

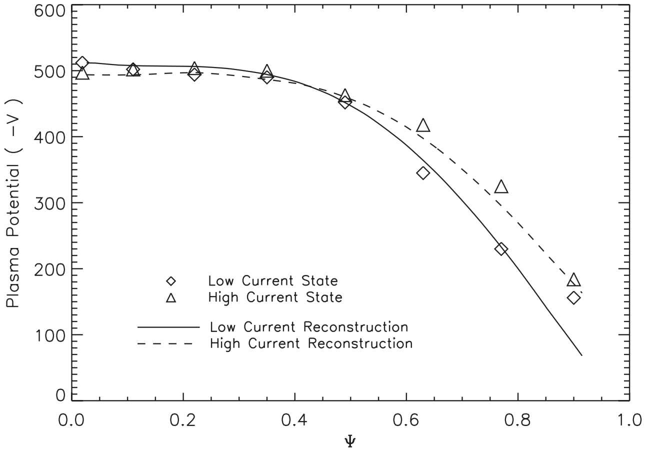

FIG. 5. The potential profile measured at a constant emitter potential $V_{\mathrm{emitter}}=525$ V in both states of a transport jump.

up to 525 V the low transport state was achieved. By ramping down to 525 V the high transport state was achieved.

Equilibrium measurements for these experiments were done using emissive (hot) and Langmuir (cold) probes.[20] For these plasmas, the plasma potential was measured with error bars of 1–2 V. Measurements of the potential profile clearly show that the equilibrium in the low and high current states are different (Fig. 5). The potential profiles imply a slightly weaker radial electric field in the high current state. The full three-dimensional (3D) equilibria were calculated by solving the Poisson–Boltzmann equilibrium equation numerically using the measured potential profiles and realistic temperature profiles based on measurements.[21,22] The temperature was approximately 11 eV in the high transport state and 15 eV in the low transport state on the inner magnetic surfaces rising on the outer surfaces, as has been observed previously.[16] With a full 3D equilibrium reconstruction, the density is known everywhere in the plasma exemplified in Fig. 6. The total electron inventory N_e is therefore known. Combined with the measured total emission current, the confinement time is then straightforwardly calculated, $\tau_c=I_{\mathrm{emission}}/eN_e$.The difference in N_e between the two confinement states was small compared to the increase in transport, so there are large differences in the confinement times of the two states. In this particular case, the confinement time in the low transport state is $\tau_c=0.9$ ms and for the high transport state it is $\tau_c=0.4$ ms. We conclude that the upward transport jumps are abrupt drops in confinement time.

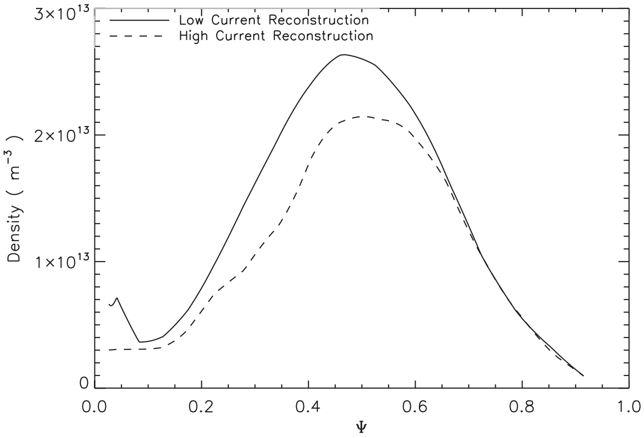

FIG. 6. The density profile in both states of a transport jump calculated from numerical reconstructions.

For all experiments described so far, the current through the cathode sheath determines when a transport jump occurs. However, transport jumps may occur without any cathode sheath physics involved. Multiple stable transport states are seen even at currents below 1 μA, far below those discussed so far. Jumps between these different transport states do not occur by varying the emission current but can in some cases be triggered by external electrostatic perturbations. For example, applying a 100 V negative bias to one sector of the newly installed conducting boundary[19] causes a jump from one transport state to another (one that has better particle confinement). During the pulse, the emission current drops abruptly and remains low after the bias is subsequently removed.

This shows that the two transport states exist independently of the cathode instability. It appears that the cathode instability provides the perturbation to the plasma that is needed for it to switch to a different transport state, and we tentatively conclude that the two transport states are experimentally realizable irrespective of the cathode sheath physics that determine when the jump happens.

To further investigate this, two emitters were carefully aligned to the same magnetic surface but physically separated by several Debye lengths, so there was no overlap of their cathode sheaths. One filament was a current controlled filament and the other was a voltage controlled filament. This setup has the advantage of keeping the plasma potential constant as a jump occurs, since the voltage on the voltage controlled filament is controlled during the jump. Since the plasma potential is closely tied to the emitter voltages, the plasma potential on the magnetic surface of the emitters is also the same before and after the jump. Since the current controlled source cannot jump, the entire jump in transport, and therefore emission current, occurs for the voltage controlled filament. Since the experimenter can control the emission current from the current controlled filament, one can trigger jumps at various total emission currents.

Consistent with our previous measurements, we observed that jumps occurred when the emission current from the voltage controlled emitter exceeded I_{crit}. Since the total current in the high transport state is independent of any sheath or emitter physics, the size of the current jump on the voltage controlled emitter should depend on the amount of current being supplied to the magnetic surface by the current controlled source. The transport physics sets the total radial loss current, i.e., the total injected current I_{total}. As one increases the amount of current from the current controlled source, the current jump on the voltage source will decrease so as to keep I_{total} for a given electron inventory the same. Before presenting the experimental data, a simple model for this process is presented to provide a basis for comparison with the experimental results.

We assume here, consistent with experimental observations, that the two transport states are represented by two

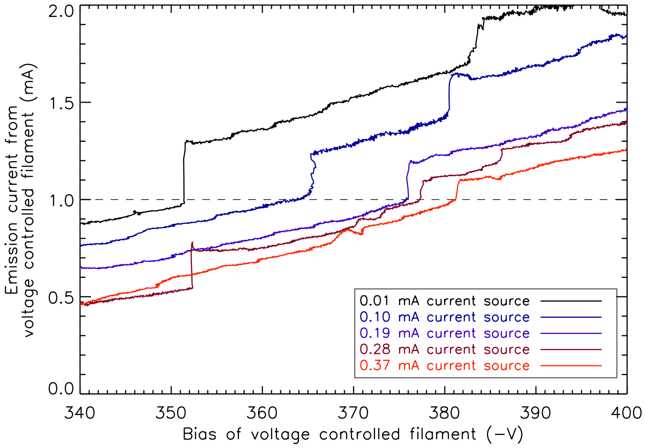

FIG. 7. (Color online) Some example emission current traces showing that the size of the jump decreases as current source current (total current) increases.

different electron confinement times, τ_1 and τ_2. Here we define $\tau_1 > \tau_2$, i.e., the confinement time is better for state 1 than for state 2. Poisson's equation implies that there should be a linear relation between the central plasma potential ϕ_{plasma} and the total charge inventory Q, so we assume $Q = C \times \phi_{\text{plasma}}$. Previously described equilibrium reconstructions show that the electron inventory is roughly the same for the two different confinement states so we can assume that C is the same in both states. A typical value for C (which is a capacitance) in CNT is $C \approx 5 \times 10^{-10}$ F. It follows that the steady state total emission current (or equivalently, electron loss rate) in state 1, I_{t1}, is

$$I_{\text{cc}} + I_{\text{vc1}} = I_{t1} = C \times \phi_{\text{plasma}}/\tau_1. \quad (1)$$

Here, the current from the current controlled source is I_{cc}, and the voltage controlled emitter current for state 1 is I_{vc1}. State 2 is described analogously.

Note that the current controlled filament has the same current before and after the jump, and the plasma has the same potential before and after the jump, whereas the current from the voltage controlled source, I_{vc}, jumps, $I_{\text{vc1}} \neq I_{\text{vc2}}$. The size of the current jump $I_{\text{vc2}} - I_{\text{vc1}}$ can be expressed in terms of the confinement times and the potential at which the jump occurs, ϕ_{plasma}:

$$\Delta I_{\text{vc}} \equiv I_{\text{vc2}} - I_{\text{vc1}} = C \times \phi_{\text{plasma}}(1/\tau_2 - 1/\tau_1). \quad (2)$$

This model predicts that if the jump is shifted to a higher plasma potential, the jump will be larger. Since the jumps occur when the voltage controlled source exceeds the critical current, jumps will occur at a higher plasma potential if the current source is supplying more current. Consequently, the predictions are that a higher current source current will lead to a jump at a higher voltage, and that the current jump will be larger. As discussed in the following, just one of these two predictions agrees with the experimental findings (Fig. 7), so at least one of the assumptions in the model is wrong.

We observed a strong ($\rho = -0.8$) and statistically significant (99%) *inverse* correlation between source current and the size of the jump, contrary to the model prediction (Fig. 7). The jumps occur at higher voltages as I_{cc} is increased, as expected. The experimental observations show that I_{t2} is nearly constant in the high transport state. Contrary to the theory described above, τ_2 is not a constant. In particular, if I_{cc} were chosen so that ΔI_{vc} were small then $\tau_2 = \tau_1$. Evidently the confinement time of the high current state can be chosen arbitrarily within the range τ_1 to τ_2 at $I_{\text{cc}} = 0$.

A significant correlation between ΔI_{vc} and I_{cc} was only observed when the emitters were aligned to the same magnetic surface in roughly symmetric locations. A reason the location of the emitters is important is that the electrons born in regions of high magnetic field strength may have a different magnetic moment and a different parallel velocity than particles born in low field regions. Therefore, these particles may have substantially different guiding center orbits. As an electron drifts out across the magnetic surfaces, it gains a large parallel energy from the decrease in electrostatic energy, but the perpendicular energy changes very little as μ is conserved and B does not vary strongly from surface to surface. Emitters at symmetric locations on the same surface will produce electrons with similar drift orbits, whereas emitters that are not in this special configuration produce electrons with substantially different drift orbits. The effect of orbits on the equilibrium is very complex and is the subject of ongoing numerical and experimental investigation. It is not possible at this point to verify with certainty that this explains our observations, but it appears likely.

That the emission current and not the confinement time characterizes the high current state suggests that it may be the detailed relation between the cathode sheath and the bulk plasma that determines the stable equilibrium states. At this point the detailed physics of the sheath-plasma interaction are not understood. One speculative explanation for the role of currents is that the cathode stability may depend on the parallel transport along the cathode's magnetic surface. The equilibrium shifts because the current from the cathode, which is initially along the field, is coupled to the perpendicular transport rate. A model like this would imply that even shifts between transport states that are not caused by a cathode instability are still strongly dependent on the cathode sheath-plasma interaction. Diagnostics are currently being developed that will allow us to diagnose plasmas without internal emitters and observe whether multiple stable transport states exist independent of the cathode sheath physics.

Transport jumps between two stable equilibrium states are very common, but we have also observed cases where there are low frequency oscillations between transport states. When the oscillations occur it is usually just before or just after a confinement jump. The oscillations represent transport rates for which there is no stable equilibrium. This situation has not yet been studied in detail.

In quasineutral plasmas upward current jumps are associated with the onset of turbulence.[1] While turbulence has not yet been studied in CNT because our current diagnostic capabilities are limited to the relatively low frequencies below about 1 MHz, we did not observe any new oscillations or increase in signal noise after a jump to a higher transport state. The low frequency oscillations in the metastable states described above occur in both low and high transport states.

V. DISCUSSION AND CONCLUSION

In the past, current jumps have been explained in terms of the action of the virtual cathode.[7] The results presented here are consistent with this effect. It is clearly demonstrated that these transport jumps occur at particular critical sheath emission currents. Current limits in diodes arise when space charge builds up forming a potential structure, a virtual cathode, that impedes the flow of electrons. At a sufficiently high current, the space-charge limit point, the potential prevents electrons from flowing through the diode.[23–25] That the jumps occur at particular local sheath emission currents is consistent with a disruption of the virtual cathode of that sheath. In our case, the anode is the equilibrium electron plasma away from the cathode sheath region. Even though the electron plasma is negatively charged, the cathode is more negatively charged or else no net emission would occur. Hence, the plasma acts as the anode for the emitter cathode in CNT.

An increase in emission is observed, not a limit to it. However, this sudden increase in emission is accompanied by a change in the equilibrium of the plasma, as revealed by the potential profile measurement. A plausible explanation for the increase in emission and the change of state follows from noting that the cathode is coupled to the plasma radial transport by continuity. The loss rate from the plasma is set by factors affecting the plasma as a whole. The neutral pressure, for example, degrades confinement by increasing the number of electron-neutral collisions everywhere in the plasma. Because the cathode is coupled to the plasma by continuity, these global transport effects can cause a conflict with the local cathode emission limits. The result is a cathode instability that drives a change from one equilibrium state, which becomes unstable to the cathode instability above a certain current, to a different equilibrium, with a greater transport rate, where the cathode is stable. There are even situations where no self-consistent solution exists and large oscillations appear continuously. By biasing a particular segment of the newly installed electrostatic boundary, it was shown that several equilibrium states can be accessed irrespective of the cathode instability, as the bias resulted in a change in confinement that persisted stably after the bias was removed.

Hysteretic current jumps have been observed in quasineutral plasmas as well. Experimental measurements in quasineutral plasmas showing that the jumps depend on the filament geometry[1] and that the jump occurs when the ion flux arriving at the cathode sheath is below a certain limit[11] and measurements of the plasma potential profiles in the stable states[2] are all consistent with a cathode instability. However, the jumps in a quasineutral plasma were caused by a different physical mechanism than the jumps described here. The basis for the jumps in quasineutral plasmas depends explicitly on ionization.[2,9] In quasineutral plasmas the jumps are the result of a transition between the anode-glow mode and the temperature-limited mode.

In the anode-glow mode, which occurs at lower currents, a virtual cathode forms between the cathode and anode that reflects low energy electrons. This mode is space-charge limited. The plasma potential beyond the virtual cathode is roughly constant until the anode sheath. Most ionization occurs in the anode sheath and the ions travel toward the cathode. As the cathode is made increasingly negative the rates of emission and ionization increase. At some critical ratio of ion and electron currents the plasma becomes unstable. The anode sheath expands to include much of the plasma volume, which increases the ionization. The ions accumulate sufficient density to neutralize the virtual cathode and remove the space-charge emission limit. Hence, the emission becomes temperature limited, referring to the temperature of the thermionic emitting filament. Bosch and Merlino[1] theorized that the onset of turbulence also causes the electron temperature to increase and the enhanced ionization rate leads to a negative differential resistance and a current jump. Sanduloviciu *et al.*[3] believed that the excitation of neutrals plays an important role by increasing the ionization cross section. None of these processes can occur in the nearly pure electron plasmas studied in CNT.

The detailed physics of these confinement jumps remains to be clarified. It has not yet been established why the measurable, but relatively small, differences in equilibrium profiles result in large changes in confinement of the electrons. The detailed physics of the cathode and its sheath and their relation to the bulk plasma surrounding the sheath are not understood at this point either. A simple model describing the jumps in terms of two confinement states described by two different confinement times was unsuccessful in explaining the jump characteristics in detail.

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